Concussion Frequency Associates with Musculoskeletal Injury in Retired NFL Players

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ABSTRACT

PIETROSIMONE, B., Y. M. GOLIGHTLY, J. P. MIHALIK, and K. M. GUSKIEWICZ. Concussion Frequency Associates with Musculoskeletal Injury in Retired NFL Players. *Med. Sci. Sports Exerc.*, Vol. 47, No. 11, pp. 2366–2372, 2015. **Objective**: Concussion is commonly associated with immediate and persistent alterations in motor function affecting postural control and gait. Patients with lower extremity joint injury have demonstrated functional alterations in the cerebral cortex, suggesting that musculoskeletal injury may be linked to alterations in brain function. Therefore, we examined the associations between concussion frequency and lower extremity musculoskeletal injury sustained during professional careers of National Football League (NFL) players in a cross-sectional study. **Methods**: An inclusive health history survey was mailed to 3647 NFL players who retired during 1930–2001. Respondents reported total concussion frequency (zero, one, two, or three or more) and presence (yes/no) of specific knee and ankle musculoskeletal injury during their NFL career. Separate logistic regression models were used to estimate associations between concussion frequency and each musculoskeletal injury type, adjusting for number of years played in the NFL, body mass index while playing in the NFL, and playing position. **Results**: Data from 2429 players (66.6% response rate) were available for analysis. Nearly 61% reported experiencing a concussion while competing in the NFL. Meniscal tear was the most commonly reported musculoskeletal injury (32%). Compared with NFL players who did not sustain a concussion, retired NFL players with one, two, or three or more concussions had between 18% and 63%, 15% and 126%, and 73% and 165% higher odds of reporting various musculoskeletal injuries, respectively. **Conclusions**: A history of concussions was associated with a history of musculoskeletal injuries during NFL careers. These data suggest that a higher number of concussions is linked with higher odds of reporting a musculoskeletal injury. **Key Words:** BRAIN, ANTERIOR CRUCIATE LIGAMENT, KNEE INJURY, ANKLE INJURY

Concussions are a common injury in American football, occurring at a rate between 0.38 and 0.42 per game in the National Football League (NFL) (3). Mild traumatic brain injury, or concussion, is described as a "traumatically induced transient disturbance of brain function and involves a complex pathophysiological process" (14). Because of the diffuse nature in which concussion affects multiple aspects of the brain, patients with a concussion demonstrate a myriad of neurological symptoms, which may include altered neuromuscular function (27,35), delayed reaction time (5,9,36), diminished postural control (19), and altered gait (2). Neurological and neuromuscular deficits after concussion may be due to injury of intracortical neurons or diaschisis, which is a loss of function of uninjured portions of the brain due to direct injury of interconnected brain areas (18).

Widespread changes in cortical metabolism that persist after concussion have been hypothesized to increase the vulnerability of the brain to a secondary insult or affect the function of complex motor patterns (8,15). Complex motor patterns require parallel function between multiple brain centers to maintain posture (13,16), initiate movement (27), and react to obstacles or perturbations (4). Inability to generate proper motor programs or refine movement errors may increase the risk of musculoskeletal injury in people competing in contact sports such as American football (25,34). Measures of postural control have been found to improve within 3–5 d after concussion (16), yet deficits in more complex postural control outcomes during gait have been demonstrated for months after concussion (20,31). Neuromuscular gait strategies known to require activation of primary and

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association areas of the motor cortex, such as braking (2) and navigating obstacles (10), have been altered up to 30 d after concussion. Impaired function of higher brain centers associated with concussion may inhibit coordinated movement patterns or impede the ability to maneuver around obstacles that may inflict injury (7,8,27); therefore, the lingering neuromuscular effects of concussion may be associated with increased risk of musculoskeletal injury sustained during sport.

Patients that have sustained multiple ankle sprains (32) and anterior cruciate ligament (ACL) injuries (33) have demonstrated deficits in the excitability of the primary motor cortex. Although these retrospective studies (32,33) are unable to elucidate whether lower extremity joint injury was a cause or effect of altered cortical function, these recent studies provide emerging evidence of a link between musculoskeletal injury and cortical dysfunction. Intercollegiate athletes with musculoskeletal injury have also displayed cognitive impairments on automated neurocognitive assessments that are similar to the cognitive impairments demonstrated after concussion (21).

In a separate study, athletes that sustained noncontact ACL injury demonstrated lower neurocognitive testing scores before ACL injury compared with athletes that did not go on to sustain an injury (38). These data suggest that neuromuscular deficits caused by a concussion may have increased the risk for sustaining a lower extremity injury. Furthermore, a preliminary study of intercollegiate athletes in the United States (16) and a recently published study on European soccer players (30) both reported higher rates of musculoskeletal injury after a concussion compared with athletes who did not sustain a concussion.

Evaluating the association between concussion history and risk of future musculoskeletal injury may provide critical information for protecting athletes from sustaining multiple injuries (concussion and musculoskeletal). Better understanding the link between brain and lower extremity musculoskeletal injuries may expose new methods for diagnosis or explain underlying areas of pathophysiology that may be relevant to both concussion and lower extremity musculoskeletal injury, thereby providing a foundation for new rehabilitation paradigms for concussion and a variety of musculoskeletal injuries that are common in sport. Retired NFL players report a high incidence of lower extremity musculoskeletal injury and concussion associated with their football career (1,17) and thus are a valuable population for examining the associations between these types of injuries. Regardless of causality, the hypothesized link between concussion and musculoskeletal injury is that altered movement due to one type of injury increases the risk of the other; therefore, the rationale for the study is to evaluate the influence that concussion history may have on lower extremity injury in NFL football players. The purpose of the current study was to examine the associations between concussion frequency and lower extremity musculoskeletal injury sustained during the professional careers of NFL players.

METHODS

Study Participants

Participants were members of The Health Survey of Retired NFL Players, an ongoing cross-sectional study that evaluates multiple aspects of self-reported health and collects injury history from retired NFL players (11,12,21). We mailed the survey to 3647 former NFL players, registered with the NFL Retired Players' Association, who retired between the years of 1930 and 2001. The survey was initially mailed to participants in May 2001 and again to nonrespondents in August 2001 and February 2002. Players that did not respond to any of the three mailings were contacted by telephone, and consenting players completed the survey with study personnel over the phone. By completing the survey, participants consented to be part of the study, which was approved by the institutional review board at the University of North Carolina at Chapel Hill (IRB #01-1490).

Health Survey of Retired NFL Players

The Health Survey of Retired NFL Players was a 13-page, paper-based questionnaire that collected player demographics, playing history (i.e., years of football played, positions played, etc.), general medical history, joint injury history, and overall health status.

Concussions. Specific to the current study, we collected the number of concussions sustained during NFL playing years. The questions regarding concussions were worded as follows: 1) "Did you sustain any concussions during your professional playing career?" and 2) "If yes, answer how many." The first concussion question required a dichotomous answer (yes or no), and the number of concussions sustained was recorded as a discrete value. For analyses, an athlete's career concussion frequency was categorized as zero, one, two, and three or more.

Musculoskeletal injury. We collected the frequency of the specific musculoskeletal injuries that were sustained during each player's NFL career. Players were asked, "During your professional football career, how many of the following injuries did you sustain?" The frequency (discrete values) of musculoskeletal injury for the following musculoskeletal injury categories was collected: 1) hamstring/quadriceps rupture, 2) medial collateral ligament (MCL) tear, 3) lateral collateral ligament (LCL) tear, 4) ACL tear, 5) posterior cruciate ligament (PCL) tear, 6) meniscus tear, 7) calf/Achilles rupture, 8) ankle ligament rupture, and 9) ankle/foot fracture. For each musculoskeletal injury, the injury frequency was categorized initially as zero, one, two, and three or more (as reported in Table 1), and for analyses examining each injury separately, these frequencies were condensed to create a dichotomous variable (zero vs one or more). To examine musculoskeletal injury more broadly, we created two body-site specific dichotomous variables (knee and ankle/foot) and a global lower extremity musculoskeletal injury frequency variable. *Knee injury* was considered

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TABLE 1. Characteristics of the sample.

Characteristics	Total Sample Mean (SD; Range)
Age at survey (yr)	53.9 (13.4; 24 to 95)
BMI at survey ($kg \cdot m^{-2}$)	30.5 (4.3; 14.8 to 56.3)
BMI during professional football career	29.4 (3.5; 15.4 to 47.5)
Change in BMI from career to survey (%)	4.3 (11.7; −47.1 to 93.9)
Total years played during professional football career	6.7 (3.5; 1 to 26)
Playing position (% (*n*/*N*))	
Lineman	40.9 (991/2425)
Linebacker or running back	25.2 (611/2425)
Wide receiver, corner back, quarter back, special teams	28.8 (698/2425)
Other	5.2 (125/2425)
Concussion frequency during professional football career (% (*n*/*N*))	
One	19.5 (473/2429)
Two	16.9 (410/2429)
Three or more	24.4 (592/2429)
Hamstring rupture frequency (% (*n*/*N*))	
One	13.9 (336/2424)
Two	5.7 (139/2424)
Three or more	6.6 (161/2424)
MCL tear frequency (% (*n*/*N*))	
One	15.1 (366/2421)
Two	5.3 (128/2421)
Three or more	1.5 (36/2421)
LCL tear frequency (% (*n*/*N*))	
One	6.0 (146/2418)
Two	1.3 (32/2418)
Three or more	1.2 (28/2418)
ACL tear frequency (% (*n*/*N*))	
One	14.3 (345/2416)
Two	2.9 (69/2416)
Three or more	1.9 (46/2416)
PCL tear frequency (% (*n*/*N*))	
One	5.8 (140/2419)
Two	0.9 (22/2419)
Three or more	1.0 (24/2419)
Meniscus tear frequency (% (*n*/*N*))	
One	18.5 (448/2416)
Two	7.4 (178/2416)
Three or more	6.4 (155/2416)
Calf/Achilles rupture frequency (% (*n*/*N*))	
One	5.0 (122/2429)
Two	0.9 (22/2429)
Three or more	0.5 (13/2429)
Ankle ligament rupture frequency (% (*n*/*N*))	
One	11.5 (279/2422)
Two	2.8 (68/2422)
Three or more	3.1 (76/2422)
Ankle/foot fracture frequency (% (*n*/*N*))	
One	11.3 (273/2422)
Two	1.8 (44/2422)
Three or more	1.9 (46/2422)
Total number of musculoskeletal injuries (% (*n*/*N*))	
One	19.8 (480/2429)
Two	15.9 (386/2429)
Three	13.1 (318/2429)
Four or more	23.0 (558/2429)
Presence of at least one injury at the knee (MCL, PCL, ACL, LCL, and meniscus)	50.2 (1213/2416)
Presence of at least one injury at the ankle/foot (Achilles rupture, ankle ligament rupture, and ankle/foot fracture)	32.6 (789/2420)

present if there was at least one injury at the MCL, PCL, ACL, LCL, or meniscus. *Ankle/foot injury* was considered present if there was at least one Achilles tendon rupture, ankle ligament rupture, or ankle/foot fracture. The *total number of lower extremity musculoskeletal injuries* variable was defined as the sum of all injury types and was categorized as zero, one, two, three, and four or more.

Covariates. We collected age at time of survey, height and weight (to calculate body mass index (BMI)) at the time of survey and while playing in the NFL, the self-reported number of years played in the NFL (discrete), and primary playing position. Primary playing position was grouped into three potential categories including 1) linemen (offensive linemen, defensive linemen, tight end), 2) linebacker and running back, and 3) wide receiver, cornerback/safety, quarterback, and special teams.

Statistical Analysis

Distributions were calculated for the following: 1) age at the time of survey, 2) BMI at the time of survey (from self-reported height and weight), 3) BMI during the football career, 4) percent change in BMI from career to survey, 5) total years played during professional football career, 6) playing position categories, 7) self-reported concussion frequency (one, two, or three or more concussions), 8) frequency of each musculoskeletal injury category (one, two, or three or more injuries), 9) total number of musculoskeletal injuries (one, two, three, or four or more injuries), knee injury (present/absent), 10) and ankle/foot injury (present/absent). Separate logistic regression models were used to estimate associations between concussion frequency (zero, one, two, and three or more) and each musculoskeletal injury type (zero and one or more), controlling for the number of NFL years played, BMI during NFL playing years, and playing position. To explore relations with the broader categories of musculoskeletal injuries, separate logistic regression models were used to estimate associations of concussion frequency (zero, one, two, and three or more) with knee injury, ankle/foot injury, and total number of lower extremity musculoskeletal injuries, adjusting for the covariates listed previously. The proportional odds assumption was tested to confirm that the association between the concussion variable and the four-level total number of lower extremity musculoskeletal injury outcome were similar across sequentially more severe levels of the outcome (i.e., the same increase in odds applies across all categories of lower extremity musculoskeletal injury). If the assumption was met, a single odds ratio was calculated. If it was not met, a generalized logit model was used to calculate separate odds ratios by musculoskeletal injury category. If the 95% confidence interval for an odds ratio included 1.0, we considered the estimate to not be statistically significant, although we considered the magnitude of the odds ratio in our assessment of the strength of associations. We calculated the test–retest reliability for the self-reported concussion and lower extremity musculoskeletal injury frequency using weighted Cohen kappa coefficient (κ) in a subset of players (n = 77) that participated in the original 2001 survey and a resurvey completed 18–24 months later.

RESULTS

Approximately 69% of the initial sample (n = 3647) returned the survey (Fig. 1). Concussion history or musculoskeletal injury data were missing in 4.8% of the 2552 participants returning the survey. Therefore, data from 66.6% of the total

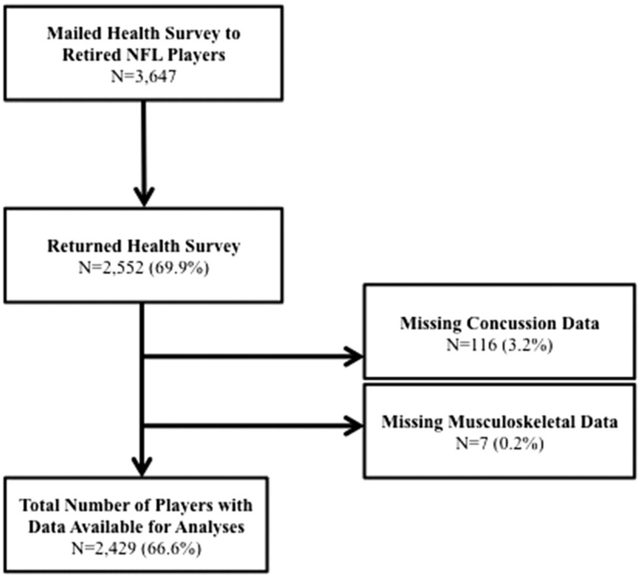

FIGURE 1—Available data for analysis. The flowchart explains how 66.6% of the total surveys mailed to retired NFL players were used for the analysis.

players surveyed could be used in this study (Fig. 1). Individual sample sizes for each question were reported in Table 1. Of the respondent sample, 60.8% reported at least one concussion and 71.8 % reported at least one of the lower extremity musculoskeletal injuries that we collected as part of the survey during their NFL career. Moderate-to-good reliability was found for self-reported frequency of concussion and all musculoskeletal lower extremity injury categories (weighted Cohen κ: concussion, 0.59; hamstring/quadriceps rupture, 0.43; MCL ruptures, 0.66; LCL ruptures, 0.49; ACL ruptures, 0.65; PCL ruptures, 0.64; meniscus tear, 0.62; Achilles tendon ruptures, 0.65; ankle ligament rupture, 0.44; ankle/foot fracture, 0.45). For musculoskeletal injury categories, knee meniscus tears were reported more frequently (32.3%) than other injuries, whereas half of the players completing the survey (50.2%) reported sustaining at least one knee injury and 32.6% of the players reported at least one ankle injury (Table 1). Achilles tendon ruptures (6.4%), PCL ruptures (7.7%), and LCL ruptures (8.5%) ranked among the least common lower extremity injuries reported to have been sustained by retired football players (Table 1). Results of adjusted analyses of the associations between concussion and lower extremity musculoskeletal injuries for the total sample are summarized in Tables 2 and 3. The proportional odds assumption was met for models including the four-level total number of lower extremity musculoskeletal injuries, and thus, a single odds ratio was calculated. Overall, a history of each of the musculoskeletal injuries was associated with history of concussions (Table 2). For analyses of one versus zero concussion, results were statistically significant for hamstrings/quadriceps rupture, ACL tear, meniscus tear, ankle ligament rupture, knee injury, ankle/foot injury, and total number of lower extremity musculoskeletal injuries. In comparisons of two versus zero concussion, results were statistically significant for all musculoskeletal injury definitions except LCL tear and PCL tear. Adjusted odds ratios were statistically significant for all musculoskeletal injury definitions in analyses comparing three with zero concussion. For each musculoskeletal injury definition, the estimates tended to be greater with an increasing number of reported concussions (e.g., for meniscus tear, adjusted odds ratios were 1.43, 2.00, and 2.32 for comparisons of one, two, and three or more concussions, respectively, with zero concussion).

DISCUSSION

Our study provides evidence of the association between self-reported concussions and musculoskeletal injuries sustained in the NFL. The overall odds of reporting a musculoskeletal injury increased when a greater frequency of concussions was also reported. Regardless of the reported concussion frequency, there was a notable increase in the odds of reporting a knee or ankle injury in former NFL players that reported any number of concussions. Associations were significantly higher for all musculoskeletal injury categories in players reporting three or more concussions. For all musculoskeletal injury categories, except for hamstring/quadriceps strains, there was a trend for increasing estimates as the number of reported concussions increased.

There is limited previous data that have evaluated the association between concussion and musculoskeletal injury (16,30). The current study provides more evidence of a potential link between concussion and musculoskeletal injury. We acknowledge that we cannot discern the causality of the association between musculoskeletal injury and concussion because it is unclear from our cross-sectional data whether the reported concussions preceded the musculoskeletal injury. Furthermore, the time between concussion and musculoskeletal injury is not

TABLE 2. Odds ratios (95% confidence intervals) adjusted for number of NFL years played, BMI during NFL, and playing position.

	Types of Lower Extremity Musculoskeletal Injury (Frequency)								
	Hamstring/Quadriceps Rupture (26%)	MCL Tear (22%)	LCL Tear (9%)	ACL Tear (19%)	PCL Tear (8%)	Meniscus Tear (32%)	Calf /Achilles Rupture 6%)	Ankle Ligament Rupture (18%)	Ankle/Foot Fracture (15%)
One concussion (19% of sample)	1.46 (1.12–1.9)	1.26 (0.95–1.69)	1.22 (0.80–1.88)	1.63 (1.23–2.18)	1.18 (0.76–1.83)	1.43 (1.12–1.84)	1.55 (0.96–2.50)	1.49 (1.08–2.06)	1.26 (0.90–1.79)
Two concussions (17% of sample)	2.14 (1.64–2.87)	1.71 (1.29–2.29)	1.52 (0.99–2.34)	1.37 (1.00–1.88)	1.15 (0.72–1.83)	2.00 (1.55–2.58)	1.65 (1.01–2.70)	2.26 (1.65–3.10)	1.77 (1.27–2.50)
Three or more concussions (24% of sample)	1.79 (1.40–2.29)	1.98 (1.53–2.56)	1.94 (1.33–2.83)	1.89 (1.44–2.48)	1.73 (1.18–2.56)	2.32 (1.84–2.92)	1.93 (1.24–2.99)	2.65 (1.99–3.53)	1.90 (1.40–2.60)

TABLE 3. Odds ratios (95% confidence intervals) adjusted for number of NFL years played, BMI during NFL, and playing position.

	Total No. of Lower Extremity Musculoskeletal Injuries (One, Two, Three, Four or More)	Presence of at Least One Injury at the Knee (MCL, PCL, ACL, LCL, and Meniscus)	Presence of at Least One Injury at the Ankle/Foot (Achilles Rupture, Ankle Ligament Rupture, and Ankle/Foot Fracture)
One vs zero concussion	1.59 (1.30–1.94)	1.36 (1.08–1.70)	1.36 (1.06–1.75)
Two vs zero Concussions	2.29 (1.85–2.83)	1.73 (1.36–2.21)	2.20 (1.70–2.83)
3+ vs 0 Concussions	2.86 (2.36–3.48)	1.92 (1.54–2.40)	2.37 (1.88–2.99)

known; therefore, we are unable to determine how risk exposure may interact with the associations between concussion and musculoskeletal injury. The specific directional and temporal nature of the association between concussion and musculoskeletal injury cannot be concluded from the current data. Previous authors have presented, in abstract form, evidence that college athletes that have sustained a concussion are 3.79 times more likely to sustain a joint injury (16). In a recent prospective study in European soccer players, Nordström et al. (30) reported that players that sustained concussions were at higher risk for sustaining other musculoskeletal injuries during the same year and in the year after the concussion. These data suggest that a concussion may initiate aberrant neuromuscular alterations that elevate the risk of musculoskeletal injury. Deficits in neurocognitive (26) and descending motor function (8,27) have been reported after concussion, suggesting that trauma to the brain can cause alterations in how patients process information and react to physical and cognitive stimuli from the environment. Although we may hypothesize that unresolved neurophysiology from a previous concussion (27) may lead to a musculoskeletal injury by diminishing the ability to execute proper movement patterns, sustaining a musculoskeletal injury may increase the risk of a future concussion. Individuals that have sustained a musculoskeletal injury have demonstrated deficits in computerized neurocognitive assessments in the first 72 h after injury that are similar to the deficits demonstrated by individuals with concussion (21). It remains unknown whether alterations in neurocognitive function after musculoskeletal injury persist for longer than 72 h, yet these neurocognitive deficits demonstrated after musculoskeletal injury might increase the risk for sustaining a concussion or amplify the symptoms after a concussive impact. The neuromuscular alterations known to occur after a lower extremity injury (39) may inhibit proper activation of the musculature that may be needed to maneuver away from a potential hazardous situation because of a lingering disability. Swanik et al. (38) demonstrated that diminished neurocognitive function was present in athletes before sustaining a noncontact ACL injury compared with athletes that did not go on to sustain an injury. These data help develop the hypothesis that inhibited neurocognition demonstrated before or after musculoskeletal injury may increase the risk of concussion by impeding a player's ability to develop and execute motor programs to avoid a potentially hazardous situation that may lead to a concussion.

Diffuse brain injury after concussion may be responsible for persistent changes in development of motor programs or initiation of voluntary movement (7,8,27), which may increase the risk of sustaining a subsequent lower extremity injury. Development of a motor program requires multiple steps including 1) processing sensory information regarding the environment, 2) integrating information in higher brain centers from memories and real-time information, and 3) initiating movement through the activation of the correct motor pathways (22). An increase in the latency to process, integrate, or initiate neuronal signals after a stimulus will affect reaction time and may inhibit the ability of player from avoiding a situation that increases the risk of injury. A concussion may cause alterations in cortical function by 1) directly damaging neurons associated with a specific function, either because of direct neuronal damage or secondary injury from swelling, and/or 2) inhibiting communication between cortical centers or impeding integration of information needed to develop a comprehensive motor program (18). Alterations in cortical metabolism after concussion may have widespread effects on multiple centers in the brain, and a subsequent diaschisis may affect information integration needed to access and incorporate memories of motor programs in the development of new motor programs or correct movement errors (18). Evidence for concussion-induced diaschisis has been demonstrated with diffusion tensor imaging (6,28), which is a magnetic resonance imaging technique that has detected alterations in white matter fiber tract integrity after concussion.

The inability for brain centers to function independently and communicate with each other after musculoskeletal injury or concussion may result in altered motor programming. Specifically, motor programs are integrated and planned in the supplementary motor cortex (29) and then propagated to the primary motor cortex of the brain for initiation of the motor program (22). Alterations in activity of the supplementary motor cortex have been demonstrated after ACL injury (23), suggesting that individuals with musculoskeletal injury may have difficulty with planning and integration of the motor programs. Decreased excitability of the primary motor cortex has been found in patients with ACL (33) and ankle injuries (32), suggesting that individuals with musculoskeletal injury may also demonstrate problems initiating motor programs. Furthermore, decreased excitability of the primary motor cortex has been demonstrated 10 d after concussion, and the excitability of the primary motor cortex recovers at a different rate compared with neurocognitive testing and resolution of concussion-related symptoms (27). Players with concussion may be advised to return to athletic participation on the basis of resolution of concussion symptoms and/or neurocognitive testing scores even though they may have an underlying inability to properly initiate motor tasks via excitation of the primary motor cortex (27). Gait navigation around an obstacle requires cortical function to process information about the obstacle, integrate information into a new movement program to avoid the obstacle, and then initiate the planned movement strategy. Gait navigation strategies have demonstrated differences 30 d after concussion, suggesting that alterations in motor function may persist after a concussive incident (10). Other cortically driven aspects of gait, such as postural control (37) or initiating a braking strategy (2), have demonstrated differences in patients with concussion. Although we have speculated on some neurophysiological factors that may link concussion to increased risk of musculoskeletal injury, mechanistic studies should be developed to best guide strategies to decrease the risk of musculoskeletal injury after concussion. Current concussion management guidelines have not traditionally endorsed a comprehensive neuromuscular evaluation of athletes with concussion to prevent future musculoskeletal injuries, yet future clinical strategies may need to be used to decrease the risk of musculoskeletal injury after concussion.

The current study provides evidence of a link between concussion and lower extremity musculoskeletal injury in a unique group of retired NFL players that were at risk for both types of injury, yet there are limitations to our study that should caution some interpretation of the data and inform future research in this area. One limitation of our concussion and musculoskeletal injury data is that they are self-reported by former NFL players. We are unable to validate our data because the NFL does not currently centralize or archive clinical medical records. There was moderate-to-good reliability demonstrated in self-reporting concussion and all musculoskeletal injury categories (weighted Cohen κ coefficient range, 0.43–0.66) over 18–24 months. The reliability of reporting concussion frequency was better when retesting after 18–24 months (weighted Cohen κ range, 0.59) than what has been previously published regarding this survey in this population conducted 9 yr apart (weighted Cohen κ range, 0.48) (24). We chose to ask about more serious traumatic musculoskeletal injury, such as "ankle ligament rupture" rather than an "ankle sprain," as respondents may not have accurately recalled minor musculoskeletal injuries and traumatic injury. Some degree of recall bias would be associated with any self-reported survey; we feel that the traumatic nature of musculoskeletal injuries that we collected as part of the current study would likely have resulted in some time lost to participation, thereby minimizing the potential that our respondents would have forgotten that these specific musculoskeletal injuries occurred. We did identify 29 individuals in the current analysis that reported being diagnosed with Alzheimer disease or dementia. We removed these individuals and performed a *post hoc* analysis and found that our results were unchanged, suggesting that including this small subset of respondents that had high risk of failing to accurately recall injury history did not affect the overall results of the current study. It is also possible that some musculoskeletal injuries were not diagnosed or were underdiagnosed during different periods in which respondents played in the NFL. In addition, we do not have information on the high school or collegiate injuries that may have been sustained in these players. Future analysis should evaluate how high school or college injuries associate with injuries sustained in the NFL, which may improve our understanding of causality between concussion and musculoskeletal injury.

CONCLUSIONS

Our study provides evidence of an association between concussion and musculoskeletal injuries in retired NFL players. After grouping the musculoskeletal injury categories, knee injuries or ankle injuries were associated with one, two, and three or more concussions. Prospective studies are warranted to confirm this association and to elucidate the underlying mechanisms driving these associations. Our study provides preliminary evidence that neuromuscular programs may be indicated to prevent musculoskeletal injury after concussion.

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No conflicts of interests are reported. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

APPLIED SCIENCES

REFERENCES

1. Brophy R, Barnes R, Rodeo S, Warren R. Prevalence of musculoskeletal disorders at the NFL Combine—trends from 1987 to 2000. *Med Sci Sports Exerc*. 2007;39(1):22–7.
2. Buckley T, Munkasy B, Tapia-Lovler T, Wikstrom E. Altered gait termination strategies following a concussion. *Gait Posture*. 2013;38(3):549–51.
3. Casson IR, Viano DC, Powell JW, Pellman EJ. Twelve years of national football league concussion data. *Sports Health*. 2010;2(6):471–83.
4. Chiu SL, Osternig L, Chou LS. Concussion induces gait inter-joint coordination variability under conditions of divided attention and obstacle crossing. *Gait Posture*. 2013;38(4):717–22.
5. Covassin T, Moran R, Wilhelm K. Concussion symptoms and neurocognitive performance of high school and college athletes who incur multiple concussions. *Am J Sports Med*. 2013;41(12):2885–9.
6. Cubon VA, Putukian M, Boyer C, Dettwiler A. A diffusion tensor imaging study on the white matter skeleton in individuals with sports-related concussion. *J Neurotrauma*. 2011;28(2):189–201.
7. De Beaumont L, Théoret H, Mongeon D, et al. Brain function decline in healthy retired athletes who sustained their last sports concussion in early adulthood. *Brain*. 2009;132(Pt 3):695–708.
8. De Beaumont L, Tremblay S, Henry L, Poirier J, Lassonde M, Théoret H. Motor system alterations in retired former athletes: the role of aging and concussion history. *BMC Neurol*. 2013:13:212.
9. Eckner JT, Kutcher JS, Richardson JK. Effect of concussion on clinically measured reaction time in 9 NCAA division I collegiate athletes: a preliminary study. *PM R*. 2011;3(3):212–8.
10. Fait P, Swaine B, Cantin JF, Leblond J, McFadyen BJ. Altered integrated locomotor and cognitive function in elite athletes 30 days postconcussion: a preliminary study. *J Head Trauma Rehabil*. 2013;28(4):293–301.

11. Golightly YM, Marshall SW, Callahan LF, Guskiewicz K. Early-onset arthritis in retired National Football League players. *J Phys Act Health*. 2009;6(5):638–43.
12. Guskiewicz KM, Marshall SW, Bailes J, et al. Recurrent concussion and risk of depression in retired professional football players. *Med Sci Sport Exerc*. 2007;39(6):903–9.
13. Guskiewicz K, Ross S, Marshall S. Postural stability and neuropsychological deficits after concussion in collegiate athletes. *J Athl Train*. 2001;36(3):263–73.
14. Harmon KG, Drezner JA, Gammons M, et al. American Medical Society for Sports Medicine position statement: concussion in sport. *Br J Sports Med*. 2013;47(1):15–26.
15. Henry LC, Tremblay S, Boulanger Y, Ellemberg D, Lassonde M. Neurometabolic changes in the acute phase after sports concussions correlate with symptom severity. *J Neurotrauma*. 2010;1:65–76.
16. Herman D, Jones D, Harrison A, et al. Concussion increases the risk of subsequent lower extremity musculoskeletal injury in collegiate athletes. *Clin J Sport Med*. 2013;23(2):124.
17. Hershman E, Anderson R, Bergfeld J, et al. National FLIaSP. An analysis of specific lower extremity injury rates on grass and FieldTurf playing surfaces in National Football League Games: 2000–2009 seasons. *Am J Sports Med*. 2012;40(10):2200–5.
18. Hovda DA. The neurophysiology of concussion. *Prog Neurol Surg*. 2014;28:28–37.
19. Howell DR, Osternig LR, Chou LS. Dual-task effect on gait balance control in adolescents with concussion. *Arch Phys Med Rehabil*. 2013;94(8):1513–20.
20. Howell DR, Osternig LR, Koester MC, Chou LS. The effect of cognitive task complexity on gait stability in adolescents following concussion. *Exp Brain Res*. 2014;232(6):1773–82.
21. Hutchison M, Comper P, Mainwaring L, Richards D. The influence of musculoskeletal injury on cognition: implications for concussion research. *Am J Sports Med*. 2011;39(11):2331–7.
22. Kandel E, Schwartz J, Jessell T. *Principles of Neural Science*. 3rd ed. Norwalk (CT): Appleton & Lange; 1991.
23. Kapreli E, Athanasopoulos S, Gliatis J, et al. Anterior cruciate ligament deficiency causes brain plasticity: a functional MRI study. *Am J Sports Med*. 2009;37(12):2419–26.
24. Kerr ZY, Marshall SW, Guskiewicz KM. Reliability of concussion history in former professional football players. *Med Sci Sports Exerc*. 2012;44(3):377–82.
25. Kiesel KB, Butler RJ, Plisky PJ. Prediction of injury by limited and asymmetrical fundamental movement patterns in American football players. *J Sport Rehabil*. 2014;23(2):88–94.
26. Kontos AP, Braithwaite R, Dakan S, Elbin RJ. Computerized neurocognitive testing within 1 week of sport-related concussion: meta-analytic review and analysis of moderating factors. *J Int Neuropsychol Soc*. 2014;20(3):324–32.
27. Livingston SC, Saliba EN, Goodkin HP, Barth JT, Hertel JN, Ingersoll CD. A preliminary investigation of motor evoked potential abnormalities following sport-related concussion. *Brain Inj*. 2010;24(6):904–13.
28. Murugavel M, Cubon V, Putukian M, et al. A longitudinal diffusion tensor imaging study assessing white matter fiber tracts after sports-related concussion. *J Neurotrauma*. 2014;31(22):1860–71.
29. Nachev P, Wydell H, O'Neill K, Husain M, Kennard C. The role of the pre-supplementary motor area in the control of action. *Neuroimage*. 2007;36(2 Suppl):T155–63.
30. Nordström A, Nordström P, Ekstrand J. Sports-related concussion increases the risk of subsequent injury by about 50% in elite male football players. *Br J Sports Med*. 2014;48(19):1447–50.
31. Parker TM, Osternig LR, Van Donkelaar P, Chou LS. Gait stability following concussion. *Med Sci Sports Exerc*. 2006;38(6):1032–40.
32. Pietrosimone BG, Gribble PA. Chronic ankle instability and corticomotor excitability of the fibularis longus muscle. *J Athl Train*. 2012;47(6):621–6.
33. Pietrosimone B, Lepley A, Ericksen H, Clements A, Sohn D. Spinal reflexive and corticomotor excitability alterations following anterior cruciate ligament reconstruction. *J Athl Train*. In press.
34. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther*. 2006;36(12):911–9.
35. Powers K, Cinelli M, Kalmar J. Cortical hypoexcitability persists beyond the symptomatic phase of a concussion. *Brain Injury*. 2014;28(4):465–71.
36. Schmidt J, Register-Mihalik J, Mihalik J, Kerr Z, Guskiewicz K. Identifying impairments after concussion: normative data versus individualized baselines. *Med Sci Sports Exerc*. 2012;44(9):1621–8.
37. Slobounov S, Cao C, Sebastianelli W, Slobounov E, Newell K. Residual deficits from concussion as revealed by virtual time-to-contact measures of postural stability. *Clin Neurophysiol*. 2008; 119(2):281–9.
38. Swanik CB, Covassin T, Stearne DJ, Schatz P. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. *Am J Sports Med*. 2007;35(6):943–8.
39. Torry MR, Decker MJ, Millett PJ, Steadman JR, Sterett WI. The effects of knee joint effusion on quadriceps electromyography during jogging. *J Sports Sci Med*. 2005;4(1):1–8.